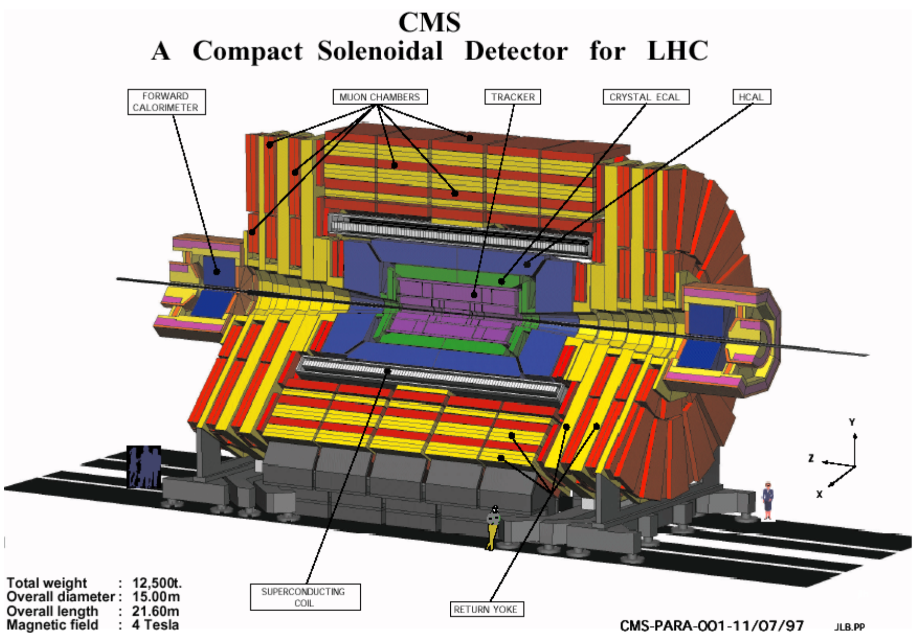
Report on the Scientific Results

JINR Participation in Compact Muon Solenoid at the LHC

Topic 02-0-1083-2009/2019



Igor Golutvin - scientific leader

Anatoly Zarubin - project leader

Sergei Shmatov - physics coordinator

- 67 participants from JINR
- 108 participants from JINR member states
- 14 paid authors and 4 unpaid authors (Ph.D. students) from JINR
- 10 paid authors and 1 unpaid authors (Ph.D.) from JINR member states

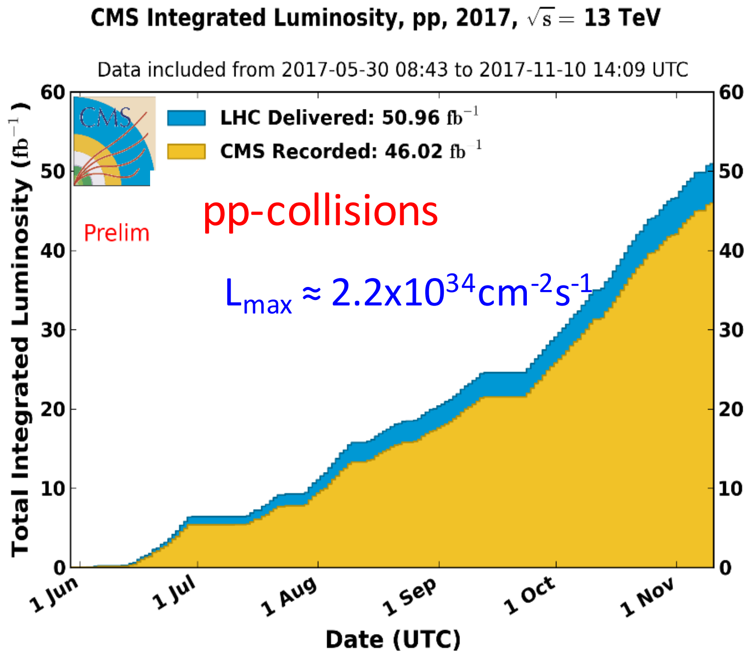
Maria Savina

on behalf of the JINR CMS Group

48th Meeting of the Program Advisory Committee for Particle Physics,
January 31, 2018, JINR, Dubna

Outline

- JINR Participation in CMS Physics Analyses, I (Standard Model Tests)
  - ✓ physics with high-mass dimuons
    - DY study in TeV energy region
    - Forward-backward asymmetry
    - Weinberg angle measurement
  - ✓ physics with jets (calibrations, charge multiplicity studies etc.)
- JINR Participation in CMS Physics Analyses, II (Search for New Physics Beyond the SM)
  - ✓ physics with dimuons (Z', KK modes of gravitons)
  - ✓ new physics in a multijet channel (BH, SB)
- Computing and Data Processing
- Summary



46.02 fb^{-1} recorded by the CMS with 90% data taking efficiency

94% of recorded data was used for the physics analysis

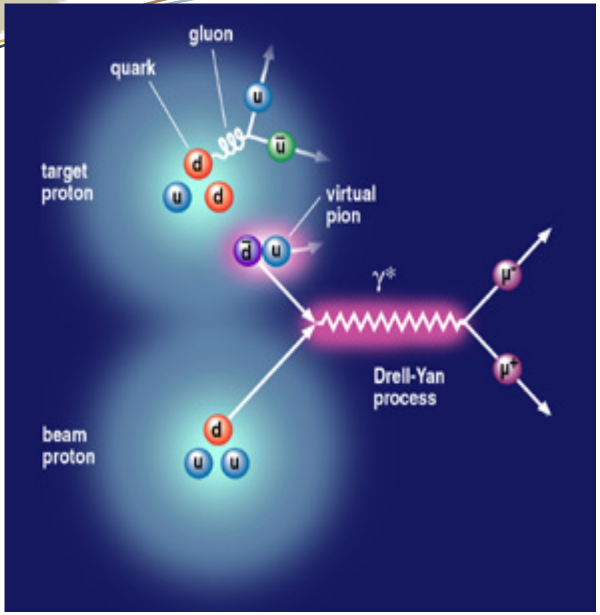
Operation efficiency of

Endcap Hadron Calorimeter - ~100%

Forward Muon Stations – 98.5%

Participation in CMS Upgrade Program is reviewed by A. Zarubin

The Standard Model: Drell-Yan Process, Higgs Boson, Charged Multiplicity



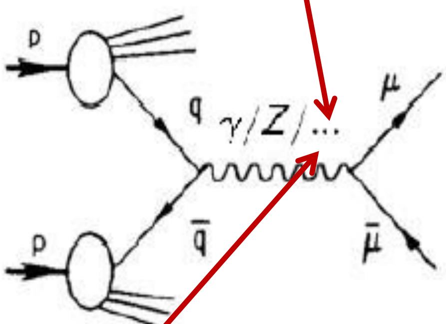
The history-steeped JINR group analyses direction for the CMS: the long way from 2002 to 2018, from physics motivations through Physics TDR 2006 up to the newest results and papers of the Run II. The work is updating permanently.

- Study of Drell-Yan process to verify the Standard Model
  - ✓ cross-sections vs invariant mass (including HO corrections, PDF etc.)
  - ✓ angular distributions (helicity structure of processes)
  - ✓ forward-backward asymmetry and weak-mixing angle

$$pp \rightarrow G_{KK}, Z_{KK}, Z' \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, jet + jet$$

- New physics and new particles in a virtual exchange channel: contributions to Drell-Yan
  - ✓ cross-sections (NP mass limits, energy scale limits, couplings etc.)
  - ✓ angular distributions (NP spin) and an asymmetry (NP model)

Heavy KK-excitations of gravitons (spin-2 state)



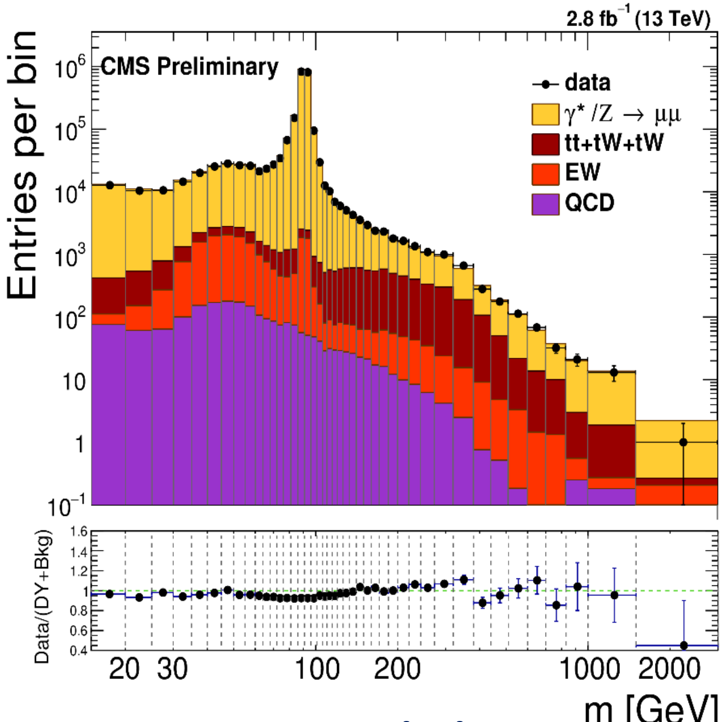
Extra gauge bosons Z′ (spin-1 state)

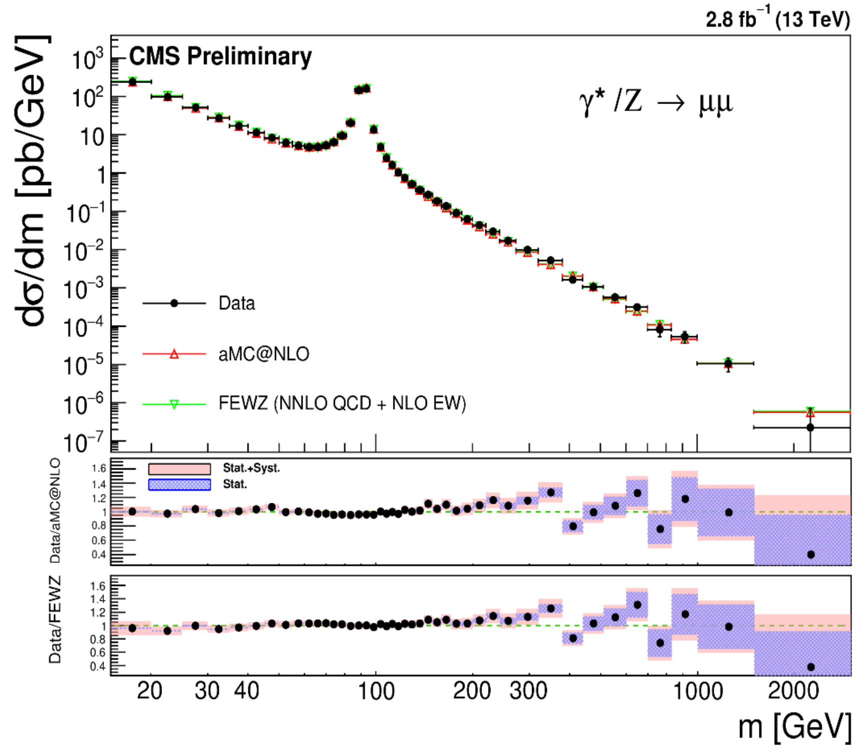
Drell-Yan: Cross-Section @ 13 TeV

Background:
EWK – from MC
QCD – from MC + estimation from data

15 < $M_{\ell^+\ell^-}$ < 3000 GeV

CMS-PAS-SMP-16-009,
CMS-PAS-SMP-17-001





Uncertainties:

efficiency (1.1-2.1%), background (K-factor and PDF) (3.6-10%), unfolding (up to 1.7 %), FSR (up to 2%), other (up to 3%), acceptance (up to 2.2 %)

Good agreement of the CMS Data and the SM predictions: aMC@NLO and NNLO QCD + NNPDF3.0 (FEWZ) + MSTW08 PDF

Results for ~30 fb^{-1} is ready, collaboration approval is in progress

1 young PostDoc +1 MSc + 1 PhD St (from JINR)

Drell-Yan: Forward-Backward Asymmetry

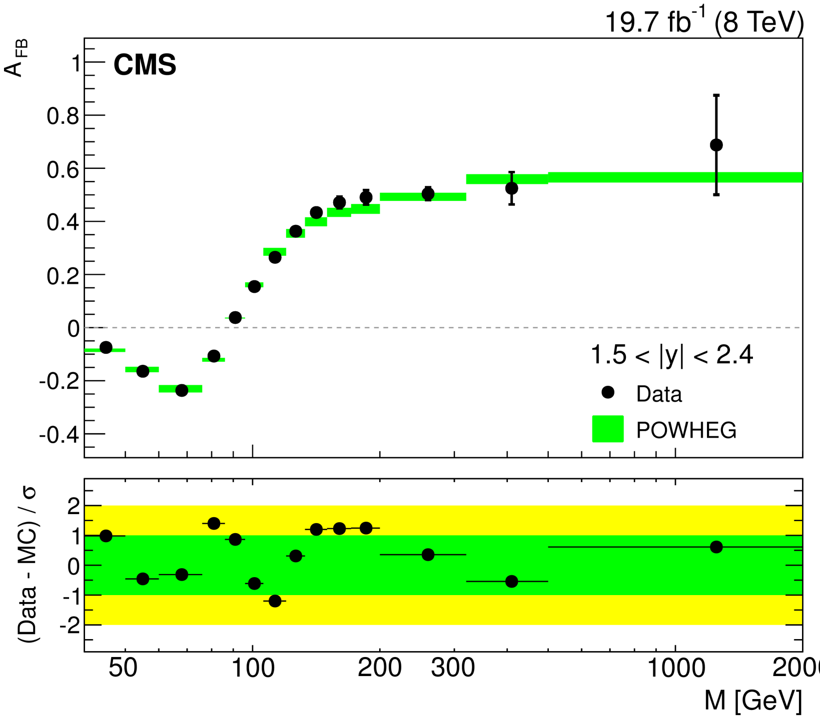
$$\frac{d\sigma}{d(\cos\theta^*)} = \frac{1}{2\left(1+\frac{b}{3}\right)}\left(1+b\cos^2\theta^*\right) + A_{FB}\cos\theta^*$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3B}{8A}$$

$$\sigma_F = \int_0^1 \frac{d\sigma}{d(\cos\theta)} d(\cos\theta)$$

$$\sigma_B = \int_{-1}^0 \frac{d\sigma}{d(\cos\theta)} d(\cos\theta)$$

EPJ. C 76 (2016) 325, CMS AN-2017/155



AFB value is sensitive to contribution both vector and axial-vector couplings

⇒ Test of SM / new physics

Data is consistent with SM

“Dilution” asymmetry measurements:

- bin-to-bin migration due to finite detector resolution
- Final-State-Radiation (FRS)
- acceptance cuts
- unknown quark/antiquark direction for the LHC

Results ~30 fb-1 at 13 TeV is coming soon

Special focus on development and comparison tools (FEWZ, SANC, READY, LPPG etc) for EWK corrections accounting (JINR + Minsk)

1 MSc + 1 PhD St (from JINR) and 1 MSc + 1 PhD St (from Minsk)

Drell-Yan yield = F [lepton angular ($\cos\theta_{CS}$), dilepton rapidity (Y), dilepton mass (s)]

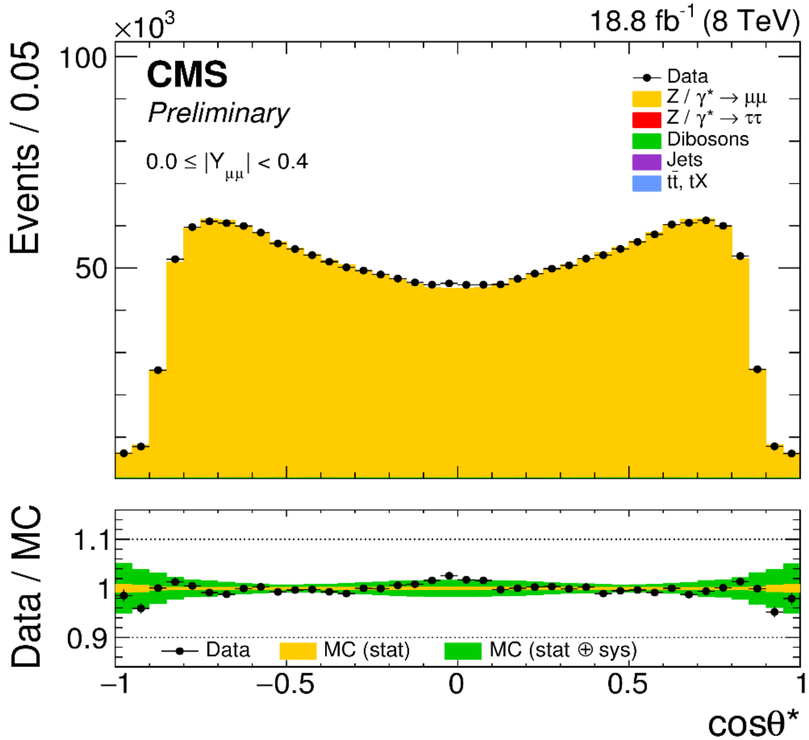
$$\frac{d\sigma_{pp\to l^+l^- X}(Y,s,\cos\theta^\star_{CS})}{dY\ ds\ d\cos\theta^\star_{CS}} \propto \sum_{q=u,d,s,c,b}[\hat{\sigma}^{even}_{q\bar{q}}(s,\cos^2\theta^\star_{CS},\sin^2\theta_{eff}) + D_{q\bar{q}}(s,Y)\times\hat{\sigma}^{odd}_{q\bar{q}}(s,\cos\theta^\star_{CS},\sin^2\theta_{eff})]\times F_{q\bar{q}}(s,Y)$$

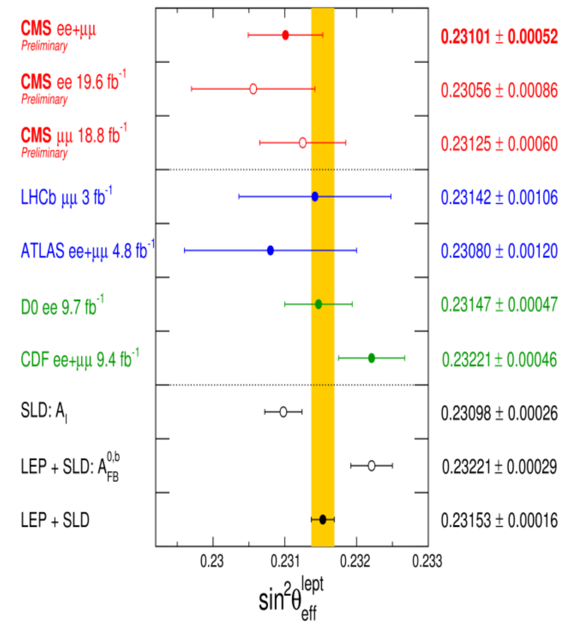
dilution factor

(reflects the fact that the quark direction is generally unknown and is taken as the boost direction of the dilepton system)

parton factor

(takes into account flavour-dependence)





CMS-PAS-SMP-16-007

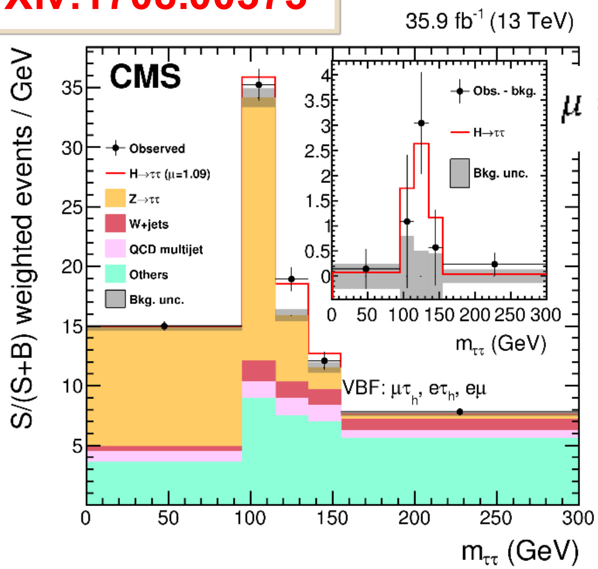
$$\sin^2\theta^{lept}_{eff} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

2012 → 2017: From first discovery with gauge bosons, to confirming fermion couplings

H → ττ observation

✦ Combination of 7/8/13 TeV → **5.9σ**

arXiv:1708.00373

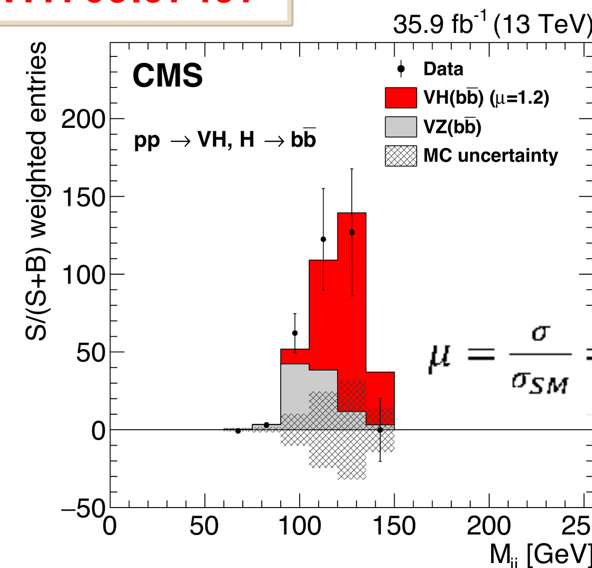


$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.09^{+0.27}_{-0.26}$$

Evidence for the H → bbar

✦ Combination of 7/8/13 TeV → **3.8σ**

arXiv:1709.07497



$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.06^{+0.31}_{-0.29}$$

1PhD St + 1 MSc (from Erevan)

SM Higgs is alive again (signal strength is agreed with SM)

Rare Higgs decays and searching extra Higgs bosons is progress

- ✓ in particular JINR involved in μ+μ- decays with b-jets (CMS AN-2016/360, updated January 2018)

Since Run2 started Higgs bosons is used for

- ✓ optimization of new calorimetry segmentation (ττ decays)
- ✓ to looks for new physics

⇨ see a talk for Upgrade of the CMS detector by A. Zarubin

Charged-Particle Multiplicities in Jets

❖ Observables:

- ✓ quark/gluon jet fractions;
- ✓ distributions of jets vs. charged-particle multiplicity (CPM) in jet;
- ✓ correlation moments of jet CPM distributions;
- ✓ density of underline event (UE).

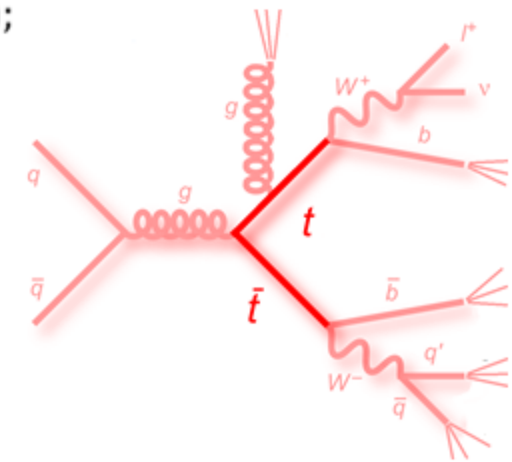
Data analysis

❖ Methodology:

- ✓ Extraction of q/g-jet fraction by q/g-discriminators;
- ✓ Correction of measured mean jet CPM (pile up jets, lost jets, low energy tracks, jet energy scale, UE density in jets);
- ✓ Unfolding of jet CPM distribution (correction for lost/fake tracks);
- ✓ Jet flavour identification, jet flavour non-universality;
- ✓ Statistical methods.

❖ Channels:

- ✓ semi-leptonic $t\bar{t}$-channel (Run-I, finished in 2017);
- ✓ dijets, gamma/Z/W+jet (Run-II, plan).



❖ Measured observables are sensitive to :

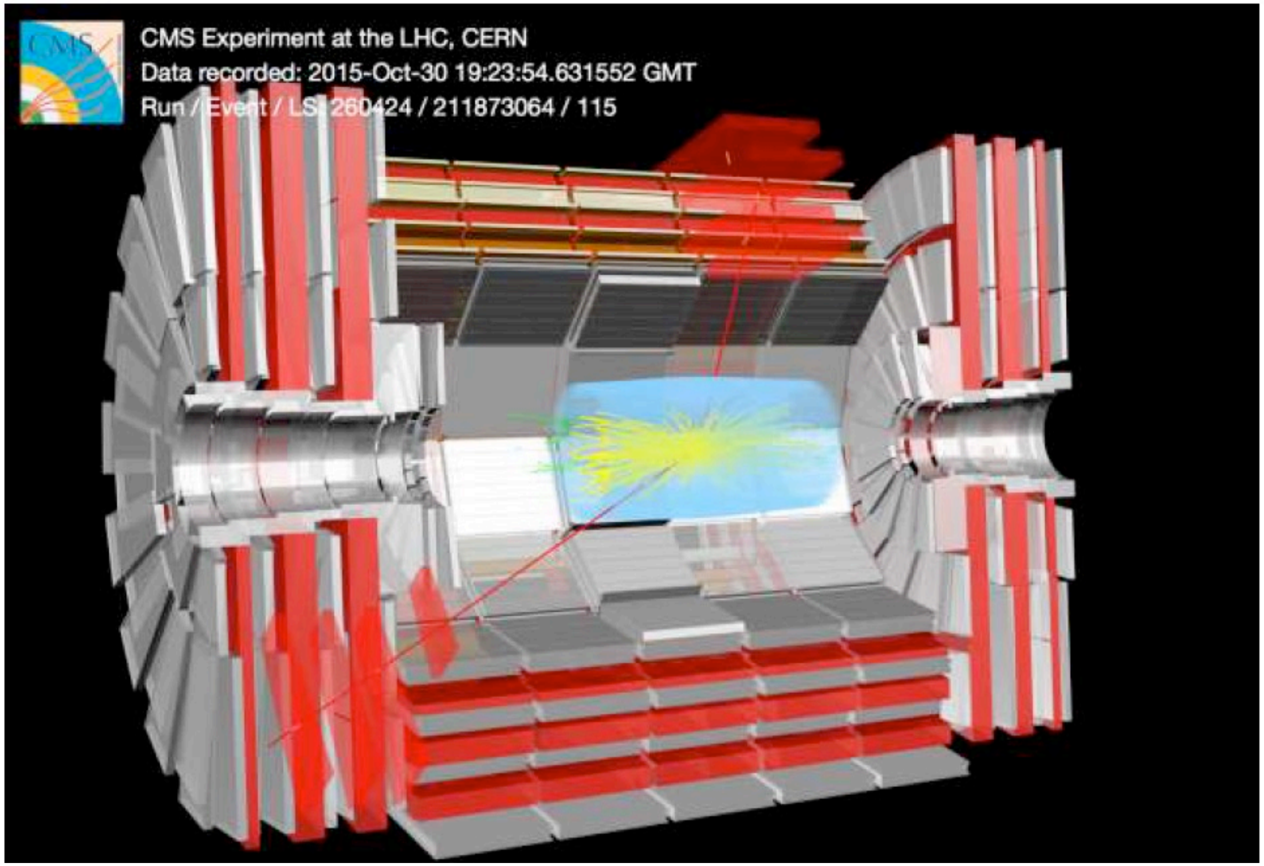
- ✓ pQCD order,
- ✓ color correlations,
- ✓ sub-structure of jets,
- ✓ models of hadronization.

Physics

+ 1 MSc (from Minsk)

New physics beyond the Standard model: TeV-scale gravity models and Extended gauge sector

$M = 2.2$ TeV Muons: $p_T = 1,\ 0.7$ TeV, $\eta = -1.36,\ 0.49$

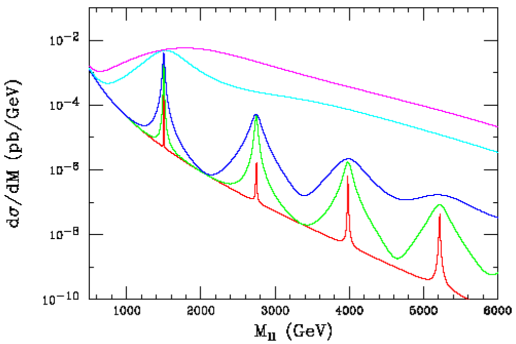


Two types of signals

KK-modes of graviton

RS1, **resonant signals**, one warped extra dimension

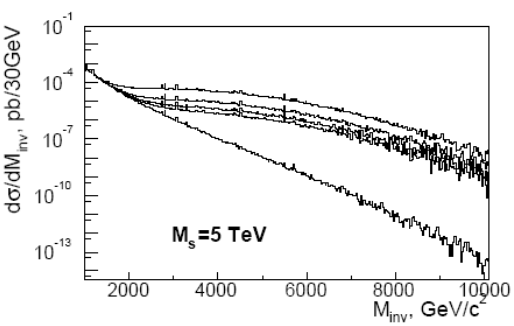
n_{ED}=1



Two control parameters of the model: curvature ***k*** ***(~M)*** and compactification radius ***r***.
A coupling constant of an effective theory: $c = k/M$, gravity scale : $\Lambda_\pi = Me^{-kr\pi}$

Not only TeV-scale gravity signals, also Z' models etc.!

ADD likes contact interactions (**non-resonant signals**), number of ED $n_{ED} = 2 \div 7$



The only control parameter in the model: scale $M_{S(D)}$.
Derivative compactification radius *r:*

$$M_{Pl} = M_S^{1+n/2} R^{n/2}$$

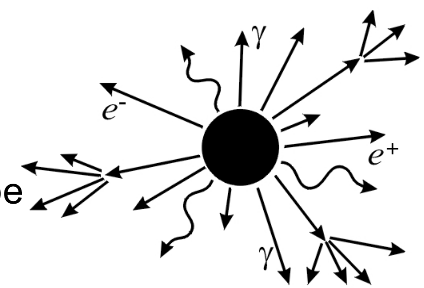
A coupling constant of an effective theory $\sim 1/M_{Pl}$

Experimental observables:
Dilepton (dijet, diphoton) spectra; jet/*l*/*γ* + missing E_T.

Microscopic black holes

Very specific signature:
Production without suppression from small coupling constant, Hawking evaporation, corrected black body decay spectrum, large multiplicity in a final state, ellipsoid shape of multiplicity distribution.
Huge number of variables in analyses (in dependence on model parameters).

Number of ED
$n_{ED} = 2 \div 7$
Entangled M_D, M^{min}_{BH}

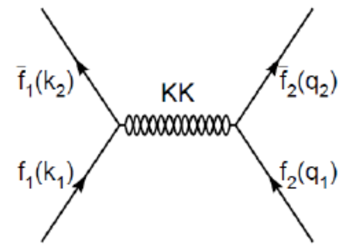


Observation of BH-type signals doesn't allow to get a fundamental multidimensional scale directly from an experiment!

Experimental observables:
Multijets/dijets,
scalar sum of the transverse energies of jets (S_T) – for BHs; flavor violating FS and an asymmetry in dijet production (like CI) – for Quantum Black Holes & String Balls.

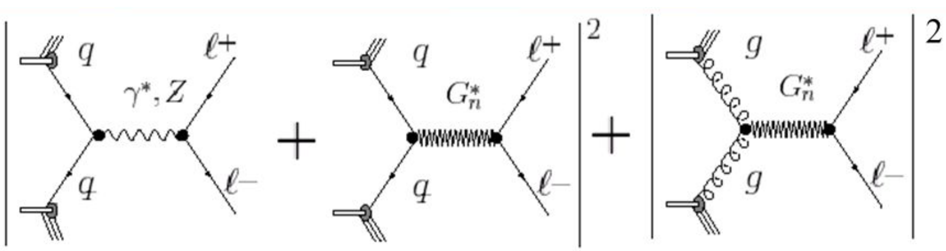
Effective field theory description, exchange by graviton KK-modes

$$\mathcal{M}_{4f}(\widetilde{h}) = -\frac{\kappa^2}{16}D(\hat{s})\left[(k_1+k_2)\cdot(q_1+q_2)\overline{f}_2\gamma^\mu f_2\,\overline{f}_1\gamma_\mu f_1 + \overline{f}_2(\not{k}_1+\not{k}_2)f_2\,\overline{f}_1(\not{q}_1+\not{q}_2)f_1 - \frac{8}{3}m_{f_1}m_{f_2}\overline{f}_2 f_2\overline{f}_1 f_1\right]$$



Effective description has a validity range of the model: $\sqrt{\hat{s}_{max}} \lesssim M_S \sim M_D$

The contribution to Drell-Yan process, full interference at the amplitude level



DY differential cross section with graviton exchange included:

$$\frac{d^3\sigma}{dM_{\ell\ell}dy\,dcos\theta^\star} = K\left(S_0 + \frac{\mathcal{F}}{M_S^4}S_4 + \left(\frac{\mathcal{F}}{M_S^4}\right)^2 S_8\right)$$

$$M_S^2 \gg \hat{s}, |\hat{t}|, |\hat{u}| \quad \hat{s} = M_{\ell\ell}^2,\; x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{s}}e^{\pm y},$$

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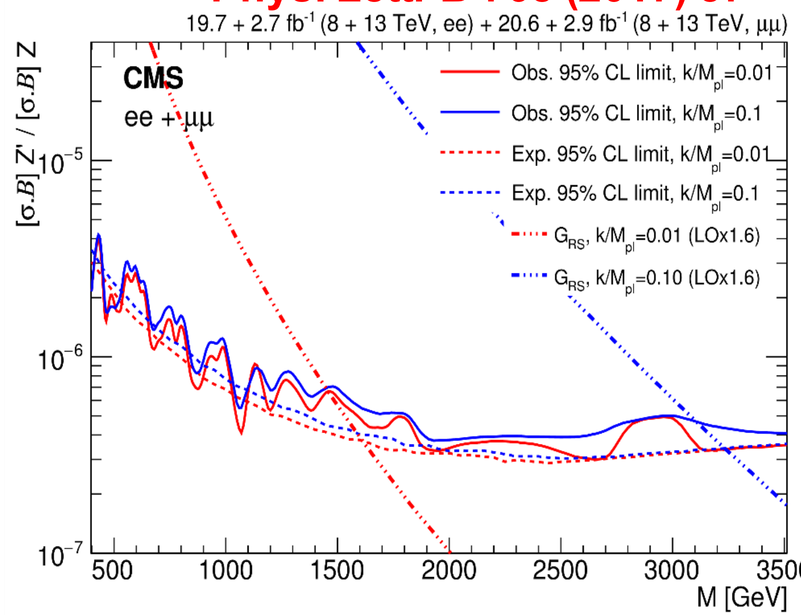


RS1 Kaluza–Klein gravitons are excluded below 1.46 (3.11) TeV for couplings of 0.01 (0.10)

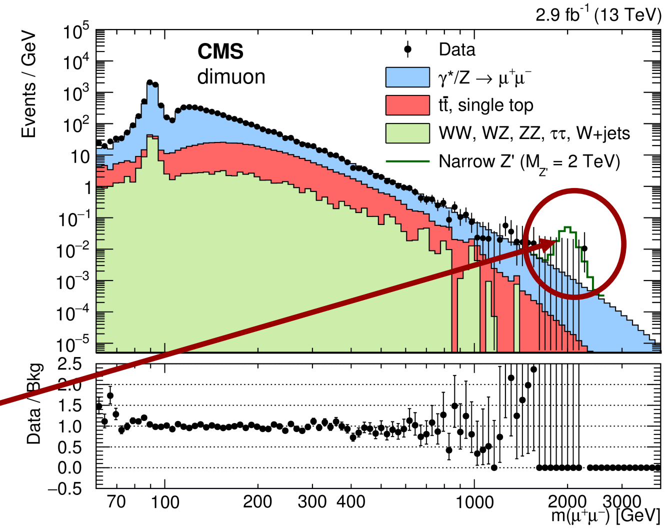
1 MSc (from JINR)

Z′ from Extended Gauge Sector

Extended gauge models based on GUT E6 or SO(10) theories or Left-Right Symmetric Models (LRM)

$$A_{ij} \equiv A(f\bar{f} \to l^+l^-) = -Qe^2 + \frac{\hat{s}}{\hat{s} - M_Z^2 + iM_Z\Gamma_Z} C_i^Z(f)C_j^Z(l) + + \frac{\hat{s}}{\hat{s} - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}} C_i^{Z'}(f)C_j^{Z'},$$

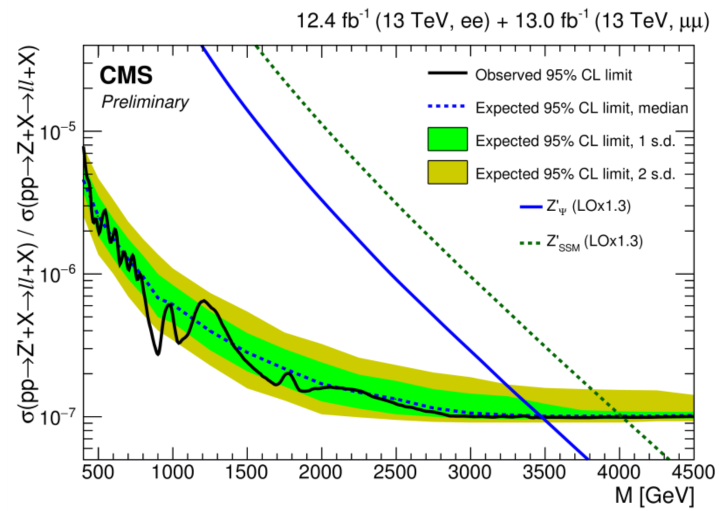
Full interference with Z^0 at the amplitude level



1. η, ψ and χ EGS models:

$$E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi$$

$$g_{Z^0}\left(\frac{g_{Z'}}{g_{Z^0}}\right)(Q_\chi \cos\theta_{E_6} + Q_\psi \sin\theta_{E_6}) \qquad -\frac{\pi}{2} \le \Theta_{E_6} \le \frac{\pi}{2}$$



2. LRM and ALRM EGS models:

$$SO(10) \to SU(3) \times SU(2)_L \times SU(1)_R \times U(1)_{B-L}$$

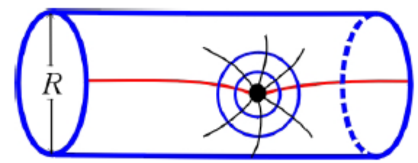
$$g_{Z^0}\frac{1}{\sqrt{1-(1+\kappa)\sin\theta_W}}[\sin\theta_W T_{3L} + \kappa(1-\sin\theta_W)T_{3R} - \sin\theta_W Q]$$

1 MSc (from JINR)

Z′ with standard-model-like couplings can be excluded below 4.0 TeV, the superstring-inspired Z′ below 3.5 TeV

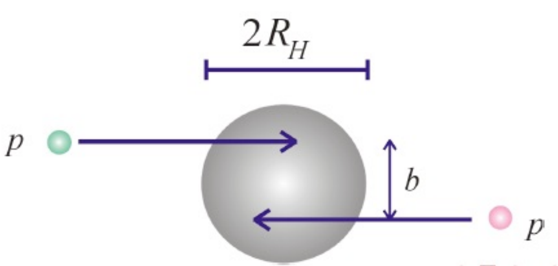
In large extra dimension models

- M_D is not a Planckian but it is about of a few TeV – reachible at the LHC
- Gravity stronger at small distances (in a full multidimensional space)
- Horizon radius of multi-D BH is larger, for M ~ TeV it increases from 10^{-38} fm (4-D black holes) to 10^{-4} fm (multi-D black holes) – can be observed

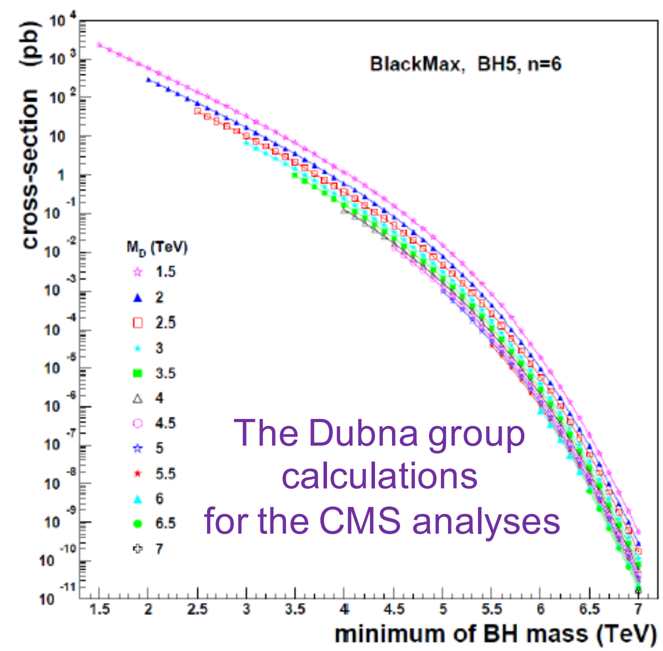


Multidimensional microscopic black hole formation

$$b < 2r_h(n, M, J)$$



For BHs with R_h<< R they are pure multidimensional objects which have approximately higher dimensional spherical symmetry



The Dubna group calculations for the CMS analyses

Differential cross section of BH production

$$\sigma_{BH} = \pi r_S{}^2.$$

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}} \hat{\sigma}(ij \to BH)|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{i,j} \int_{M_{BH}^2/s}^{1} \frac{dx_i}{x_i} f_i(x) f_j\left(\frac{M_{BH}^2}{s x_i}\right)$$

Black Holes: Multiparticle Production @ 13 TeV

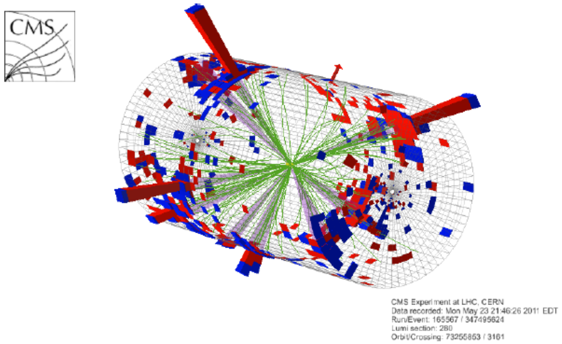
Phys. Lett. B 774 (2017) 279

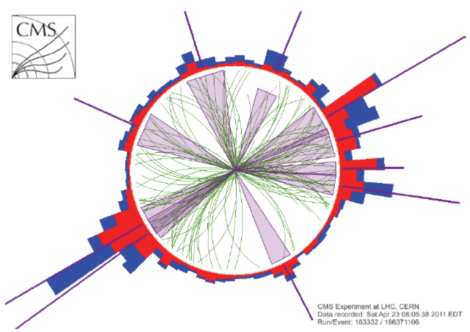
BH production
8 physically different scenarios used, more then 750 signal samples to scan the parameter space

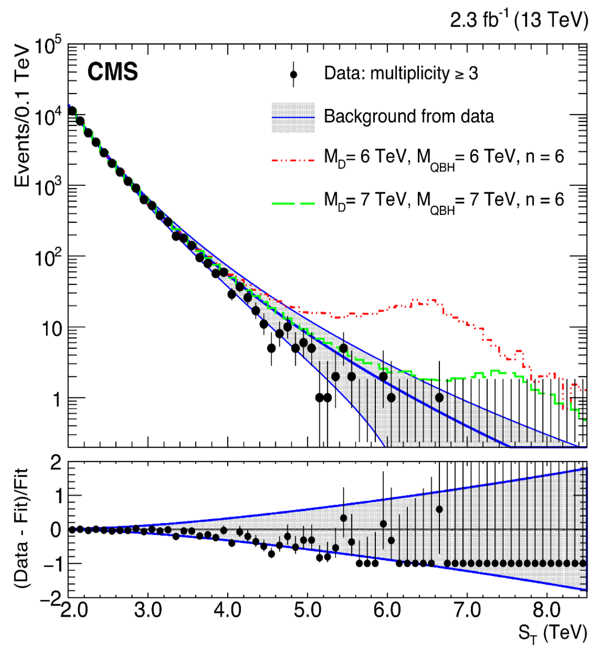
The discriminating variable between a signal and a dominant QCD multijet background is the **scalar sum of the transverse energies** of all reconstructed objects in the event, $\mathbf{S_T}$

$$S_T = \sum_{i=1}^{N_{jet}} E_T$$

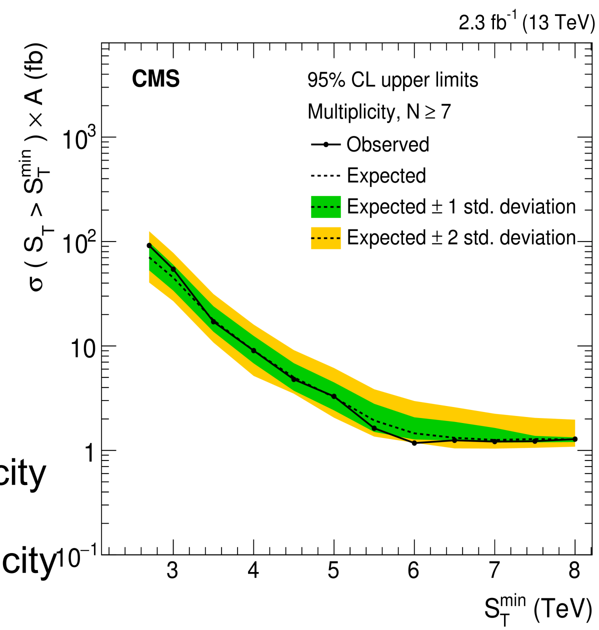
Jets, photons and leptons, $E_T > 50$ GeV, missing $E_T > 50$ GeV







Upper limits at 95% CL on the multijet production cross section: *N* ≥ *2–11*



The JINR group participates in this CMS analyses (and initiates this work in part) since 2009.

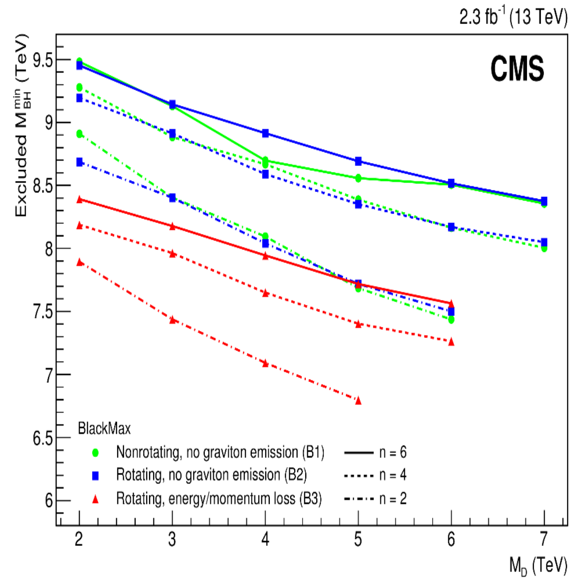
The shape of the S_T in low-multiplicity data is used to predict the QCD multijet background in high-multiplicity signal regions.

1 PhD St + 1 MSc (from JINR)

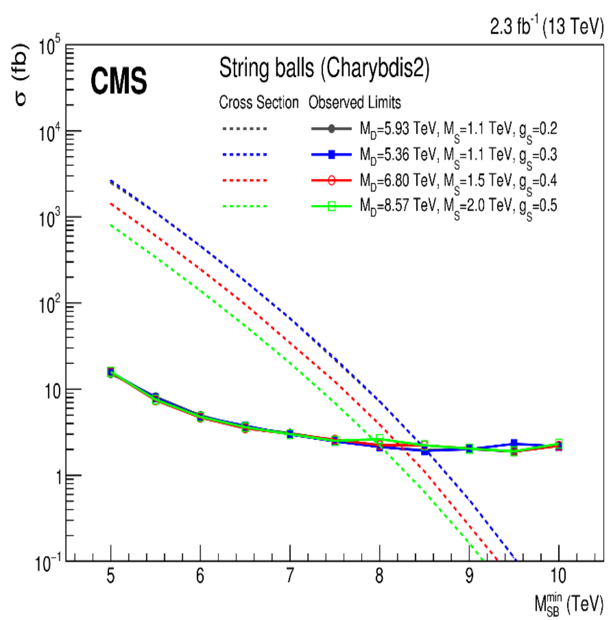
Black Holes: New Limits @ 13 TeV

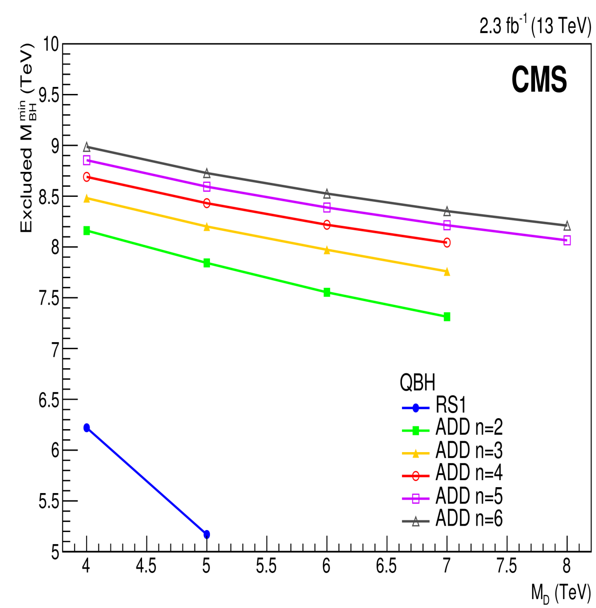
Phys. Lett. B 774 (2017) 279

- ✓ we exclude minimum semiclassical BHs masses below 7.0–9.5 TeV
- ✓ lower limits on the minimum quantum BH mass span the 7.3–9.0 TeV range for the ADD (n >2) and 5.1–6.2 TeV range for the RS1 (n=1)
- ✓ for the case of the string balls, the mass exclusion limits reach 8.0–8.5 TeV



Use Charybdis, BlackMax, QBH generators to realize the different theoretical scenarios





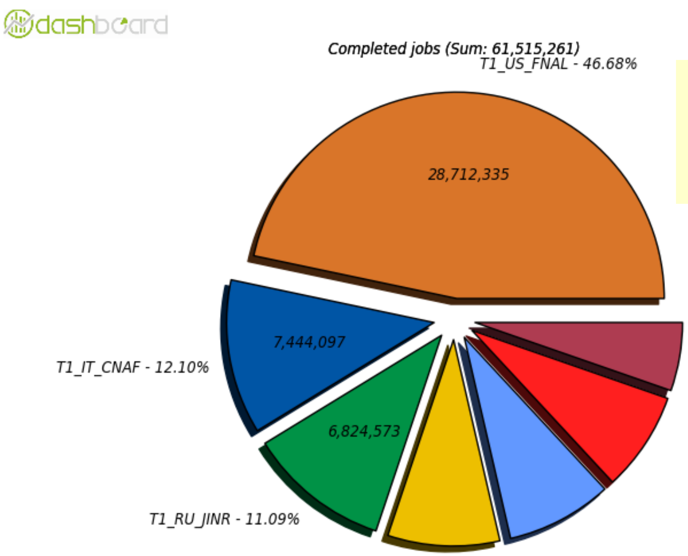
Results (Black Holes and Sphaleron) for 35 .9 fb^{-1} is ready, collaboration approval is in progress

1 PhD + 1 MSc (from JINR)
+1 PhD + 1 MSc (from Erevan)

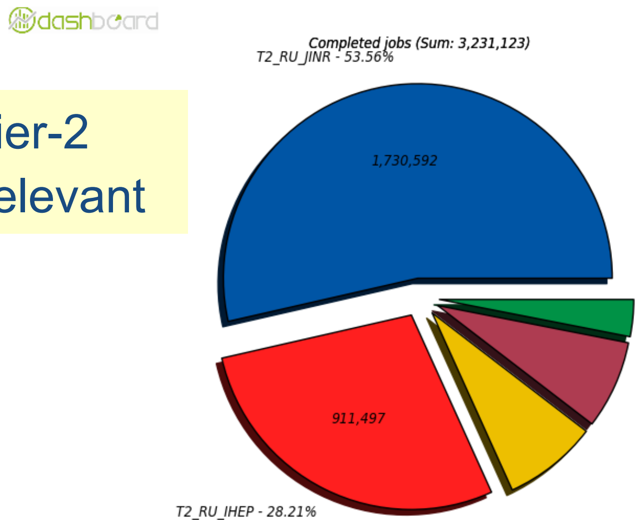
The development of the CMS experiments data processing system is developed in parallel with the Physics and Upgrade Programs.

It is necessary to provide the experiments with the long-term storage petabytes of data and the facility to process and analyze the data.

The JINR are actively involved in study, utilization, and development of both the Tier-1 and Tier-2 sites to ensure full-scale participation in CMS data processing and analysis for the JINR physicists, JINR Member States, and whole RDMS CMS Collaboration.



JINR Tier-1/Tier-2 are stable and relevant



JINR Tier-1 provides ~11% of Tier-1 CMS performance (completed jobs)

JINR Tier-2 provides above 53% of RDMS Tier-2 Computing facilities (completed jobs)

2015-2017 data @ 13TeV (up to ~ 2-13 fb-1)

– Search for High-Mass Resonances Decaying to Dilepton Pairs in pp Collisions at 13 TeV (Phys. Lett. B 768 (2017) 57, CMS AN-2016/391, Oct. 2017)
– Search for Microscopic Black Holes at 13 TeV (Phys. Lett. B 774 (2017) 279)
– Drell-Yan pair production: x-sections, AFB etc. (CMS AN-2017/155)
– Higgs μ+μ- decays with b-jets (CMS AN-2016/360, updated January 2018)

Above 163 papers were published in J. High Energy Phys, Phys. Rev. Lett., Phys. Lett. B, Eur. Phys. J. based on data of Run1-Run2

18 authors from JINR (4 PhDs) + 11 from DMS

5 public papers and 2 CMS PAS

6 review papers

18 talks for the CMS (5 talks by the PhD stud.)

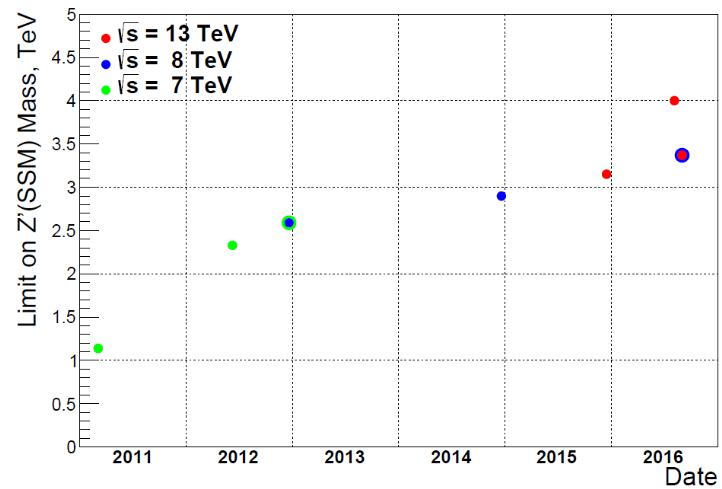
1 PhD thesis

2012 data @ 8TeV analyses were fully completed (up to ~ 20 fb-1)

– except for charged-particle multiplicities in quark and gluon jets at 8 TeV (not approved yet)

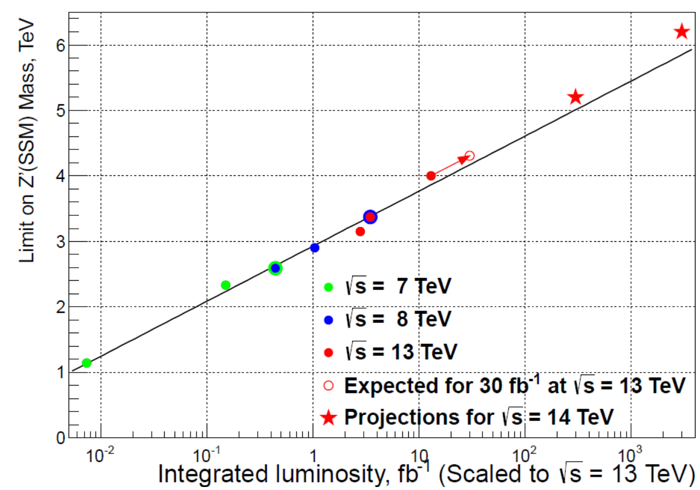
The CMS analyses based on 2015-2017 data are almost completed

~ 167 papers are published or submitted to publish, many analyses are going to be public



JINR participation in the CMS is very successful: JINR physicists are involved in whole CMS chain from data taking (shifts) and to final data analysis

- ✓ we contributed in six CMS physics analyses
  - 5 CMS public papers
  - 6 review papers
  - 18 talks for CMS
- ✓ young physicists are involved actively



The first-priority JINR physics tasks include long-term campaigns to look for new physics with

- ✓ Di-muons (since 2002)
- ✓ Multijet studies (since 2009)

In 2018 (and beyond) we expect plenty of results on 13 TeV beams with above 100 fb^{-1} !

Thank you for your attention!

Backup Slides

Основные формулы для ЧД

Для случая ADD

$$r_{S(h)} < R_c$$

(R.C. Myers and M.J. Perry, Ann. Phys. 172, 304, 1986)

$$r_h^{(n)} = \left[\frac{\mu}{1+(a/r_h^{(n)})^2}\right]^{\frac{1}{n+1}} = \frac{r_s^{(n)}}{\left[1+(a/r_h^{(n)})^2\right]^{\frac{1}{n+1}}}.$$

$$r_S^{(n)} \equiv \mu^{1/(n+1)}$$

$$r_S^{(n)}(\sqrt{\hat{s}}, n, M_D) = f(n) M_D^{-1}[\sqrt{\hat{s}}/M_D]^{1/(n+1)},$$

$$\sqrt{\hat{s}} = M_{BH}$$

$$f(n) \equiv \left[2^n \pi^{(n-3)/2} \frac{\Gamma[(n+3)/2]}{n+2}\right]^{1/(n+1)}.$$

$$r_S = \frac{1}{\sqrt{\pi} M_D}\left[\frac{M_{\text{BH}}}{M_D}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)\right]^{\frac{1}{n+1}}$$

Для случая RS1 при условии

$$r_S \ll 1/k e^{-k r_c}$$

$$\Downarrow$$

$$\tilde{M} < E < (M/k)^2 \tilde{M}$$

$\sigma \sim E/\tilde{M}^3$ как для ADD с n=1.

Дополнительные ограничения по энтропийным критериям для ЧД RS-типа (x_{min} > 16)

$$S_{\text{BH}} = \frac{4\pi}{n+2}\left(\frac{M_{\text{BH}}}{M_D}\right)^{\frac{n+2}{n+1}}\left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)^{\frac{1}{n+1}}$$

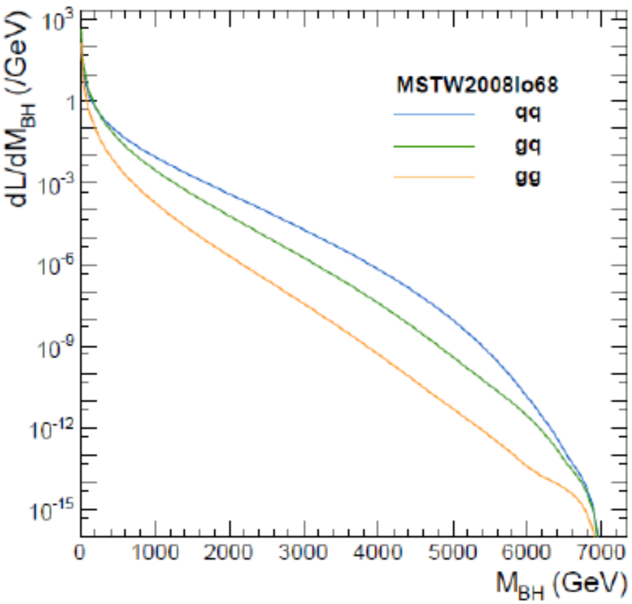
$$S = \frac{1+n}{2+n}\frac{M_{BH}}{T_H}$$

$$T_H = M_D\left(\frac{M_D}{M_{BH}}\frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)}\right)^{\frac{1}{n+1}} \times \frac{n+1}{4\sqrt{\pi}} = \frac{n+1}{4\pi r_S}$$

Рождение ЧД – геометрическое сечение

Шварцшильдовский радиус

$$r_S = \frac{1}{\sqrt{\pi} M_D}\left[\frac{M_{BH}}{M_D}\left(\frac{8\Gamma(\frac{n+3}{2}}{n+2}\right)\right]^{\frac{1}{n+1}}$$



$$\sigma_{BH} = \pi {r_S}^2$$

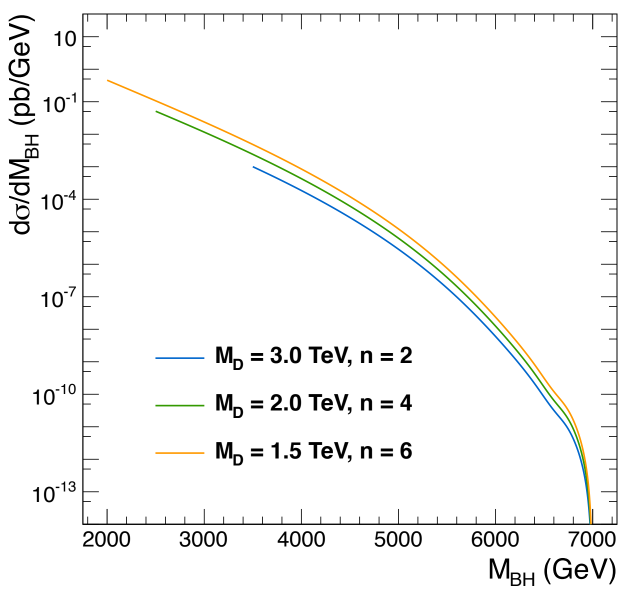
– классический непертурбативный процесс

В предположении, что вся начальная энергия столкновения удержана под горизонтом

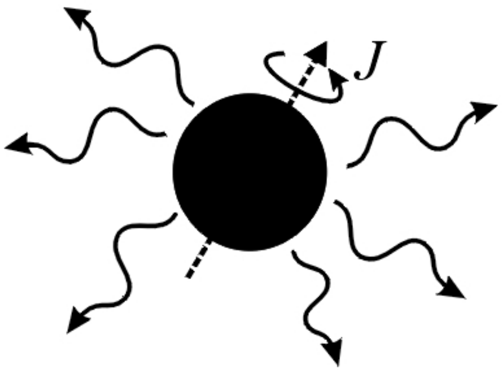
$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}} \hat{\sigma}(ij \to BH)|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{i,j} \int_{M_{BH}^2/s}^{1} \frac{dx_i}{x_i} f_i(x) f_j\left(\frac{M_{BH}^2}{sx_i}\right)$$

$$\hat{s} = x_i x_j s$$

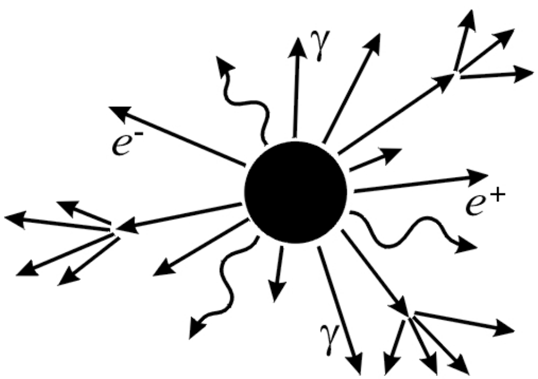


Evolution Stages for BH



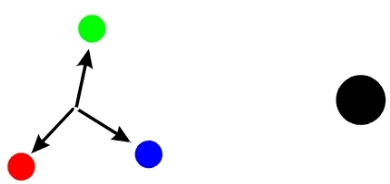
I. Balding phase

Asymmetric production, but "No hair" theorem: BH sheds its high multipole moments for fields (graviton and GB emitting classically), as electric charge and color.
Characteristic time is about $t \sim R_S$
Result: BH are classically stable objects



II-III. Hawking radiation phases (short spin down + more longer Schwarzschild)

Quantum-mechanical decay trough tunneling, transition from Kerr spinning BH to stationary Schwarzschild one. angular momentum shedding.
After this – thermal decay to all SM particles with black body energy spectra. Accelerating decay with a varying growing temperature. No flavor dependence, only number of D.o.f.– "democratic" decay
Correction with Gray Body Factors



IV. Planck phase: final explosion (subj for QGr)
BH remnant (non-detectable energy losses), N-body decay, Q, B, color are conserved or not conserved